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# AGILITY : HISTORY, DEFINITIONS AND BASIC CONCEPTS

Patrick LE BLAYE  
ONERA

System Control and Flight Dynamics Department (DCSD)  
Base Aérienne 701, 13 661 Salon Air, FRANCE

## SUMMARY

The purpose of this presentation is to provide some engineering basis of the concept of agility.

We'll see that the definition of agility has evolved across recent aviation history, from the well known area of airframe agility to a global concept of operational agility.

We'll give some consensus definition, some of which have been proposed by the working group 19 of the Flight Mechanics Panel of AGARD.

We'll briefly examine the concepts of agility relative to each component of the system (airframe, systems, weapons) and give some orders of magnitude of present and future weapon systems performances, which may have particular consequences on the human in flight.

We'll then examine the concept of operational agility and conclude with some perspectives for potential areas of preoccupation relative to the role of human pilots in the future combat scenarios and information environment.

## 1. INTRODUCTION

Recent aircraft prototypes such as the X-31 or Su-35 have demonstrated impressive flying capabilities and astonishing maneuvers, which first come to mind when one speaks of "agility". The technical feasibility of such agile airframe and its tactical utility under particular combat conditions is now widely acknowledged. Future aircraft will probably integrate some technologies directly derived from these prototypes, such as thrust vectoring and flight controls integrating new devices. Those technologies result in an extension of the flight envelope and possible maneuvers; they may pose new requirements on the pilot.

Less spectacular but probably much more influential are the emerging technologies (calculation power, sensors, datalinks,...) and the new tactical environment (multi forces, multi role, multi targets,...) which contribute or push to enhance the agility of each component - airframe, but also avionics and weapons - of the combat system used by the human pilot.

This high level of agility of each component is obviously desirable and it should result in an increase of the global agility of the combat system, which requires special attention from the engineers. Moreover, global agility results in an always increasing information flow made

available to the pilot and which has to be efficiently used in order to fulfill the mission.

## 2. HISTORICAL DEFINITIONS

Generally speaking, agility is defined as the quick moving of a body or of the mind.

The historical background reveals an evolution of the concept of agility or similar concepts applied to highly maneuverable aircraft. This evolution is of course linked with the progress of aircraft technologies and with the consecutive extension of flying capabilities.

### 2.1 Supermaneuverability and post stall flight

Before agility, supermaneuverability was first defined, as the "ability to fly in the post-stall regime".

The post stall regime is the domain of flight at high angles of attack.

In the conventional regime, angle of attack is limited to low values, where lift increases almost proportionally with the angle of attack.

In the post stall regime, lift no longer increases but decreases with the angle of attack. So, the aircraft trajectory may go down while the aircraft nose is high, and the actual aircraft trajectory may become difficult to perceive for the pilot.

Also, aircraft capable of controlled flight at high angles of attack usually have very efficient control devices and demonstrate high angular rates, which make rapid changes of the flight trajectory possible.

These facts are illustrated in another definition of supermaneuverability, which "refers to the unusual flight trajectories presently investigated by high performance fighter aircraft" [1].

Flying at high angles of attack raises difficult problems in terms of aerodynamic behavior, propulsion and flight controls. It requires a powerful and sophisticated integrated control system so that the aircraft can be effectively flown by a human pilot. The progress in computer power was a *sine qua non* for opening this new domain of controlled flight.

It has to be noted that the post stall regime is necessary synonymous of low speed flight, which makes its practical utility somewhat questionable and probably limited to particular combat conditions, such as closed-in combat at one versus one.

However, historically, the research necessary to extend the flight domain of some prototypes to the post stall regime has widely contributed to the progress in the reliability of the flight control systems installed on most modern aircraft and in their handling qualities at low speed, which is needed also in critical traditional flight phases such as take off and landing.

## 2.2 Agility, super agility and hyper agility

The notion of agility appears with the generalization of naturally unstable flown-by-wire aircraft and the development of thrust vectored prototypes. Those aircraft exhibit high maneuverability and turn rates even at high angles of attack and an extended flight envelope, sometimes including the post stall regime.

Many similar definitions exist and are now well accepted to define the airframe agility [2] :

"Ability to shift from one maneuver to the other" (Col. Boyd, 1986)

"Time rate of change of the aircraft velocity vector" (W.B. Herbst, 1988).

Next, a more general definition emphasize the shift of the concept of agility towards global agility, including the role of each element of the system into its efficiency :

"Ability of the entire weapon system to minimize the time delays between target acquisition and target destruction" (A.M. Skow, 1989).

This recent concept of global agility was used in various studies on the practical impacts of agility, sometimes with slightly different denominations : weapon system agility, full envelope agility, practical agility, operational agility.

For instance, a parametrical study on the tactical utility of new technologies such as post stall flight, enhanced radar coverage and agile missiles addressed the full envelope agility ; its results emphasize the need for the balance and proper integration of the various components of the weapon system, including aircraft, armament, avionics and pilot [3].

Only a few references exist for the denominations of super agility or hyper agility [4]. These denominations could be understood as either augmented agility or supermaneuverability (post stall) plus agility, but it seems that they may lead to some confusion and that there is no need for new terms, unless they relate to a particular new technology or capability.

## 3. RECENT DEFINITIONS

In recent years, the Working Group 19 of the Flight Mechanics Panel of AGARD [5] made a considerable effort to synthesize the various and sometimes differing viewpoints on the topic of agility.

This group eventually identified several possible aspects of agility and provided some consensus definitions as follow :

*Airframe Agility* : the physical properties of the aircraft which relate to its ability to change, rapidly and precisely its flight path vector or pointing axis and to its ease of completing that change.

*Systems Agility* : the ability to rapidly change mission functions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.

*Weapons Agility* : ability to engage rapidly characteristics of the weapons and its associated onboard systems in response to hostile intent or counter measures.

*Transient Agility* is a continuously defined property reflecting the instantaneous state of the system under consideration.

*Operational Agility* : the ability to adapt and respond rapidly and precisely, with safety and poise, to maximize mission effectiveness.

The quickness and precision are critical elements of all these definitions.

The concept of Operational Agility was established with the essential intent to provide definitions and metrics appropriate to capture the role of the component parts of the weapon system and their interaction, as the main contributor to the global effectiveness of a complex aircraft design.

The Working Group 19 also covers the pilot-vehicle interface and finally give some recommendations, two of whom are directly related to the human consequences of agility :

- Establish the Influences on Awareness of High Rate and Acceleration Maneuvers.
- Establish the Influence of Prolonged Exposure to Sustained 'g' at Moderate Levels.

In the following chapters, we will briefly examine the concepts of agility relative to each component of the system (airframe, systems, weapons) and give some orders of magnitude of nowadays and future weapon systems performances, which may have particular consequences on the human in flight. We will then examine the concept of operational agility and conclude with some perspectives for potential areas of preoccupation relative to the future combat scenarios and tactical environment.

## 4. COMPONENTS AGILITY

### 4.1 Airframe Agility

#### 4.1.1 Two complementary considerations

Airframe agility relates to its ability to change, rapidly and precisely its flight path vector or pointing axis and to its ease of completing that change.

This definition covers two complementary considerations :

- maneuverability, the ability to change magnitude and direction of the velocity vector, and
- controllability, the ability to change the pointing axis through rotation about the center of gravity, independent to the flight path vector ( Figure 1).

In the common sense, those considerations are sometimes conflicting and, indeed, they reveal that agility is the result of a compromise in the aircraft design : on one hand, it is desirable for the aircraft to be able of high peak velocities and turn rates, i.e. to have a high maneuverability, and in the same time it is highly desirable to be able to precisely control those parameters, which is obviously easier to obtain when the peak values are limited.

As such, airframe agility relates closely to, and may be

regarded as an extension to, flying qualities. The considerations above are related to the distinction classically made in flight dynamics between, respectively, the study of aircraft performance and the study of handling qualities.

The airframe agility may or not include the aircraft ability to fly and to maneuver at high angles of attack, also described as the post stall flight region, which give rise to new problems to the designer (aerodynamic stall, propulsion ignition, non linear and non stationary behavior, unstable configuration, control of the possible departure).

This ability to fly at very high angles of attack may also pose some specific problems to the pilot, for instance to perceive what is the actual flight path of the aircraft. This problem is partially due to the technical difficulty to present the direction of the velocity vector on a display with a limited field of view. Some possible future solutions will be covered in the pilot-vehicle interface chapter of this lecture.

This problem is also clearly due to a necessary change into the basic flying habits of ordinary pilots. On light aircraft, the primary flight parameter is the aircraft body pitch angle ; it is visually controlled and the consequence of any change on the flight path is also visually controlled. On aircraft equipped with a head up display and an inertial navigation unit, the direction of the velocity vector is usually displayed. It is used for

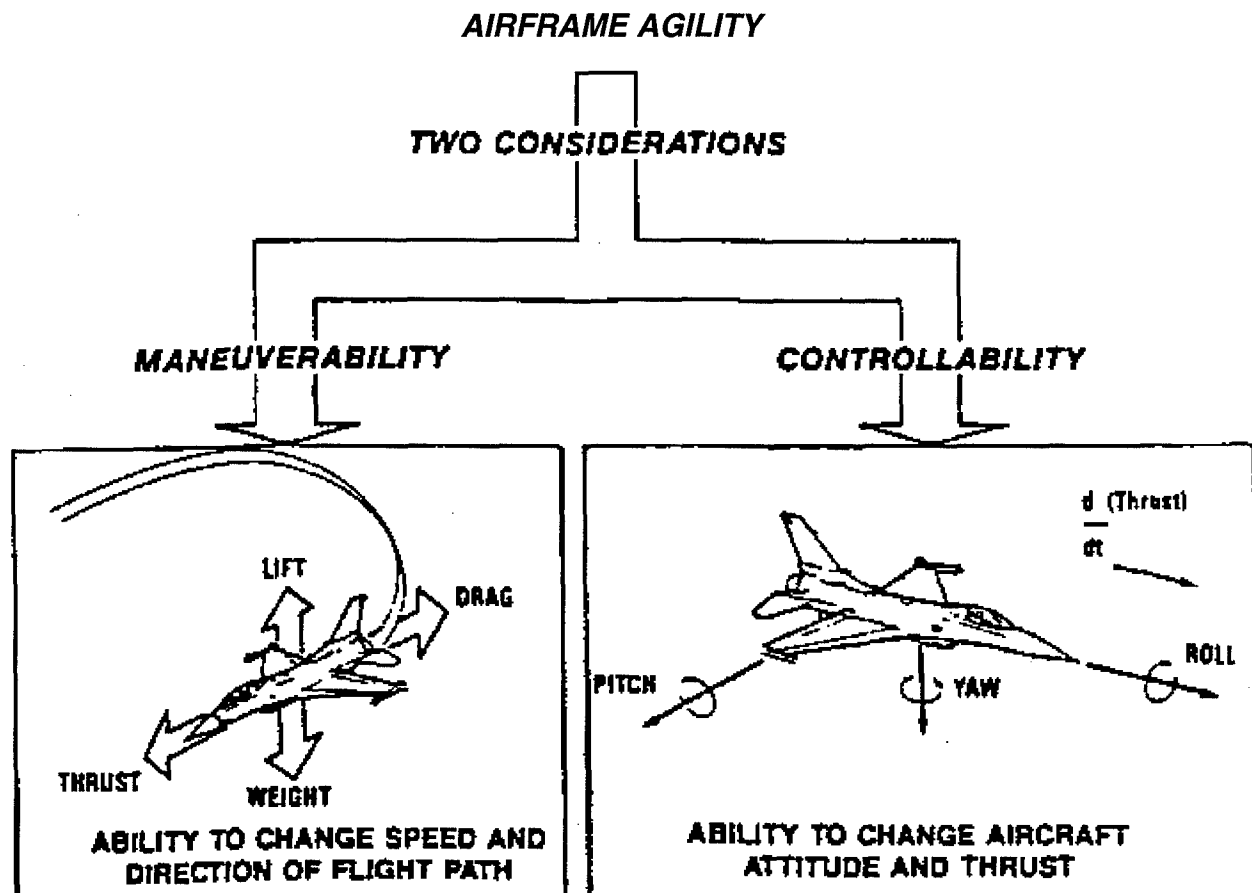


Figure 1 : Airframe agility : maneuverability and controllability.

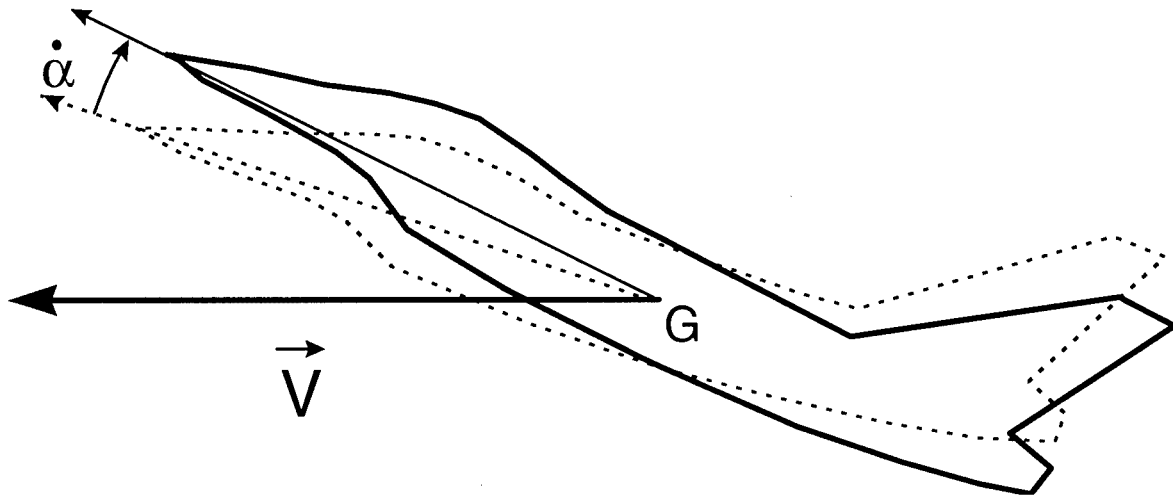


Figure 2 : Longitudinal agility.

instance when achieving a precise head up landing. Pilots usually get used quite easily to this new way of piloting, there is no deep conflict between body and velocity axis because the angular difference are still limited. On an agile aircraft flying at very high angle of attack, the body axis and the velocity axis may get completely decoupled, resulting in a complete difference between the perceived aircraft attitude and the actual path, which are no longer linked by the traditional flight equations.

Some similar problem may occur as soon as a technology is introduced that radically extend the possible solutions available for the pilot to achieve a given goal. This class of problem will be addressed in the chapters of this lecture dealing with psychological aspects, and selection and training.

#### 4.1.2 Longitudinal, torsional and axial agility

In order to derive human consequences of airframe agility, it may be useful to consider separately some of the main components of this agility. Different definitions and reference systems are available to achieve this goal. They're introduced below.

Three axis are frequently used to describe the agility relative to the velocity vector rotation/change into the body axis :

- Longitudinal agility : rate of change of the angle of attack, up and down (Figure 2).
- Torsional agility : velocity vector roll rate (Figure 3).
- Axial agility : rate of change of the velocity.

Longitudinal agility (pitch up) is related with the ability to rapidly point the nose of the aircraft. This ability is necessary in air combat as it allows to align and shoot a target, once an appropriate relative position has been acquired. In the conventional regime, an increase of the angle of attack means a reduction of speed and an increase of the load factor. The rate of change of the load factor is called the G onset. G onset up to 15 G/sec might be obtained on modern fighters. The maximum G onset level is a critical parameter of a possible pilot's loss of consciousness, together with the duration of the exposure to the maximum G level.

Longitudinal agility (pitch down) is linked with the ability to quickly recover speed, for instance after a shooting maneuver has been achieved. This ability is

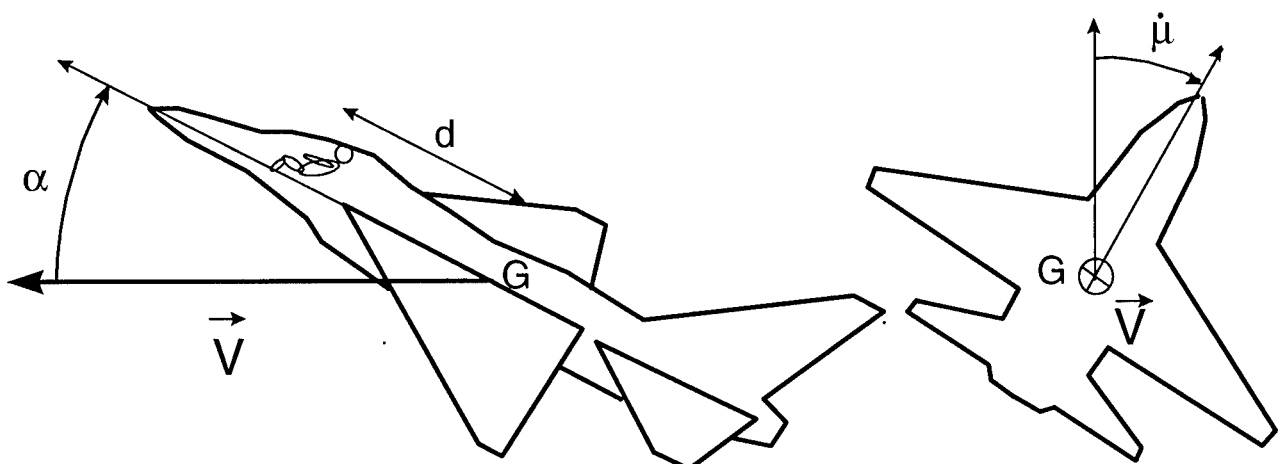


Figure 3 : Torsional agility.

absolutely necessary if high angle of attacks are to be used, because the aircraft at low speed is very vulnerable.

Torsional agility is relative to the roll rate around the velocity vector, with a constant angle of attack and with zero sideslip. The roll rate around the velocity vector is considered rather than the roll rate around the body axis. At small angles of attack, those rates are almost identical, but at high angles of attack, the control of the velocity vector roll rate allows a better decoupling of the aircraft attitude with the aircraft flight path. The velocity vector roll rate results from a combination of the body axis roll and yaw rates, which is achieved by the flight control system. The side slip angle is usually maintained at the value of zero, in order to reduce the aerodynamic drag. When the angle of attack is high, the velocity vector roll is perceived as a yaw by the pilot. Any change in the velocity vector roll rate results in a lateral load factor applied to the pilot. The value of this lateral load factor depends on the distance between the aircraft center of gravity and the location of the pilot's seat.

Axial agility is necessary in order to quickly accelerate, for instance once a target has been detected and has to be intercepted, or once a low speed combat maneuver has been achieved. It is obviously primary linked to the maximum thrust available and also to the engine response delay, from the time the throttle is pushed forward to the time the thrust actually reached the corresponding value. This delay depends on the engine regulation and inertia. Also, the tolerance of the engine to abrupt changes of the throttle position is certainly an important characteristic of axial agility.

Nowadays, the common design of aircraft control laws aims to give the pilot the direct control of those three components independently.

It has to be noted that each of these three components of agility is not directly linked with one particular component of the acceleration vector (noted  $G_x$ ,  $G_y$ ,  $G_z$  in the aerodynamic reference system). The relationship between one control component and the actual acceleration response depends on the flight control system. At a first glance, one can only give some general rules : the longitudinal command is usually the load factor/ $G_z$  acceleration at high speed and the angle of attack at low speed (below corner speed) ; the lateral command is the velocity vector roll rate, which results in a mix of  $G_y$  and  $G_z$  accelerations ; the engine command is primarily linked with  $G_x$  acceleration with a  $G_z$  component at high angles of attack or when thrust vectoring is available.

The effects of each acceleration component into the pilot's body axis of reference obviously depends on the position and on the inclination of his/her seat.

#### 4.1.3 Nose pointing versus velocity vector pointing

Another distinction among the components of the airframe agility can also be introduced with some benefit in order to assess the practical influence of agility :

- the nose pointing agility is the primary effect of a change of the aerodynamics or thrust controls, and
- the velocity vector agility is a secondary effect of the nose pointing agility, chronologically speaking.

This distinction is particularly appropriate when evaluating the influence of agility on the weapons employment. When firing the aircraft gun, the pilot has to point the aircraft nose towards the target : the gun firing opportunities are obviously related to the nose pointing agility. When they are launched at a high - limited- angle of attack, conventional missiles "fall into the wind" because of their natural stability. So, the pilot trying to launch a conventional missile has to orient the velocity vector to the target otherwise the missile may break lock after launch : the missile launch opportunity are first dependent on the velocity vector agility.

These considerations are of course directly linked with the capability of the weapons. For instance, future missiles may be launched under adverse conditions (high AOA) or unlocked, which may modify the requirement to orient the aircraft or the velocity vector before launch.

#### 4.1.4 Technologies for airframe agility

Among the enabling technologies for airframe agility, the following are of primary importance :

- Aerodynamic design (configuration, control surfaces),
- Propulsion design (air intakes, engine tolerance),
- Thrust vectoring (pitch only or pitch and yaw),
- High Thrust to Weight ratio, key characteristic for the aircraft capacity to quickly recover its energy,
- Flight Control laws and systems (fly by wire).

Now almost in operation, the thrust vectoring allows a substantial increase of the maximum pitch up and pitch down rate, as shown by the flight test results of the YF22 aircraft (Figure 4).

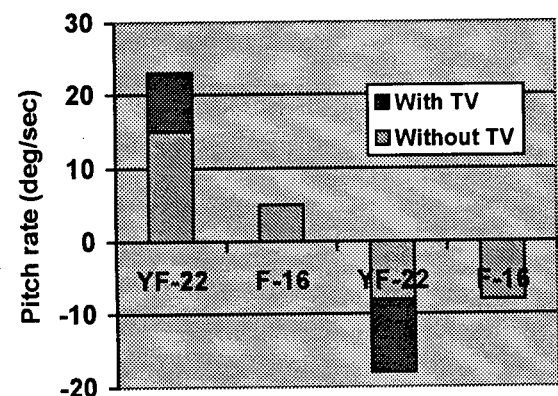


Figure 4 : Maximum pitch up, pitch down of the YF22 aircraft [6].

The thrust vectoring also contributes to an increase of the maximum roll rate (Figure 5). This is due to the fact that thrust vectoring, even if pitch only, allows a substantial relaxation of the constraints over the aerodynamic control surfaces, which can then be used to control the roll rate, while the pitch attitude is controlled by thrust vectoring.

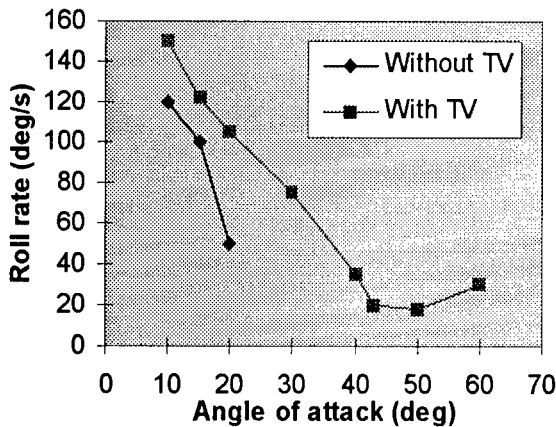


Figure 5 : Maximum roll rates of the YF22 aircraft, with and without thrust vectoring [6].

Thrust vectoring may be available on most future aircraft as a baseline or as an option. Studies and flight test are on the way for most programs currently under development (GRIPEN, F22, JSF, SU37 export).

In fact, the thrust vectoring technology has two main possible applications :

- improve the handling qualities and expand the flight envelope (high agility, post stall flight, STOL),
- or exploit this new control device to reduce traditional control surfaces (canards and tail) and thus, reduce drag and improve stealth.

One can suppose that a key concern for the aircraft manufacturers is to determine the best possible trade-off between agility and stealth.

#### 4.1.5 Controls implications of airframe agility

The aircraft controls consist of the pilot's inceptors primarily used to handle the aircraft. They are primarily related to the aircraft flying qualities.

An high airframe agility may be achieved by adequate aerodynamic design and by various devices, such as extra aerodynamic control surfaces, forebody vortex control, pitch-only or pitch-yaw thrust vectoring. The number of elementary controls devices, the dynamics required to control the aircraft in the unconventional flight regime (high angles of attack), the non-linear behavior of the aircraft in those conditions, the necessary adjustments of the engine air intakes, together with the natural instability of the airframe necessary to achieve high maneuverability, are all numerous factors which require a sophisticated and integrated flight control system.

#### 4.1.6 Towards a carefree handling system

Whatever the means used to obtain the airframe agility, the philosophy underlying the design of the flight control system may differ from one country or from one aircraft manufacturer to the other.

Some aircraft provide good examples of an original control philosophy :

- Thrust vectoring independent control (HARRIER, SU37 TV). In aircraft such as the Harrier/AV8, the ability to independently vector thrust was designed primarily to achieve vertical or short take-off and landing performance (STOL). Subsequently, the ability to vector in forward flight was also demonstrated as a possible combat technique which provides rapid deceleration and extra lift [7]. However, the requirements for post stall maneuverability are quite different : pitch and yaw axis moments generation is then required, together with rapid response rates which make an integrated flight/propulsion system mandatory. The ability to engage and disengage thrust vectoring may be required in particular situations, such as degraded flight modes, but pilots are probably most likely to benefit from integrated, rather than independent, control when it is engaged. This is demonstrated for instance by the research programs conducted on the basis of the HARRIER aircraft experience, involving integrated flight control of thrust vectored aircraft [8].
- Departure-tolerant aerodynamic design (MiG 29, SU 35). The preferred philosophy among these particular designs is to allow the pilot to fly in the post-stall region while being able to recover from the spin, rather than to build limiters into the flight control system [9]. The intent is to be able to use the entire envelope in combat and to teach the pilot how to recover from unstable situations (possibly with the help of an auto recovery system, as the panic button existing on the MiG 29 aircraft).

Having considered those particular designs, a general agreement is now that a system integrating flight and propulsion control is likely to bring substantial benefits in terms of ease of use of the aircraft and also in terms of safety and mission effectiveness.

Such a carefree handling system enables a limited number of controls (stick and throttle) to be used to maneuver the aircraft inside the whole flight envelope and it takes care automatically of the aircraft limitations.

For instance, once selected, operation of thrust vectoring is transparent with the flight control system dividing the required controls deflections between the thrust vectoring and conventional control surfaces. The system may also limit the stick inputs so that the load factor never exceeds the aircraft structural limits, given its current configuration.

The carefree system may improve flight safety, as it makes it possible to avoid aircraft departure and loss of control in most flight conditions.

Safety and flying accuracy can be further improved by implementation of advanced functions such as :

- automatic recovery from unusual situations,
- ground proximity warning,
- obstacle and collision avoidance,
- exit gate and aided post stall termination,
- optimized maneuvers, e.g. for energy recovery.

Carefree handling makes it easier for the novice pilot to fly the aircraft. This is now a key advantage as the formation and training flight hours are reduced. Also, a side effect of the carefree control system is that the aircraft can be flown more aggressively, without any limitations on the control stick input.

On the other hand, expert pilots have a tendency to find it frustrating because their flying proficiency is not recognized as it used to be. Anyway, the pilot job in the future will obviously comprise more management and decision tasks than basic flying.

As the basic flying workload is reduced, the pilot can better concentrate on the tactical decisions and actions. Spatial orientation and situation awareness are also supported by carefree handling, as less attention is required to the primary flight information displays.

#### 4.1.7 Lessons learned from the X-31 experience

The X-31 program provides a good example of a carefree integrated flight control system : the design goal was to allow controlled flight and carefree maneuvering at and beyond stall boundary, without any additional workload in the post stall region [10].

This is achieved by use of three thrust-vector vanes, plus four trailing edges flaps and an all-moving canard. These control effectors were all integrated into an advanced flight control system.

The control law was designed to control the aircraft in the flight path axis system :

- load factor command up to 30 degrees AOA and angle of attack command when in post stall (PST), i.e. above 30 degrees AOA,
- velocity vector roll rate command (with zero sideslip),
- sideslip command (below 40 degrees AOA).

The handling quality requirements consist of high pitch and velocity vector rates (pitch rate up to 25 degrees/sec and velocity vector roll rate between 30 and 50 degrees/sec in PST, i.e. for an angle of attack ranging from 30 to 70 degrees) plus precise fine tracking for gun aiming.

Those objectives can be quite conflicting because of the large angle of attack domain ; they require a careful design of the control system and gains. For instance, the longitudinal stick sensitivity in the X-31 was so high that it was possible to command high AOA even when you really do not need it. This was corrected by the addition of a pilot selectable AOA limiter into the flight control software [11].

Also, a problem appear during the flight trials of the X-31, with the pilots hitting their legs with the stick when commanding high roll rates at high AOA. A scaled lateral stick command was implemented into the software to solve the problem.

Some possible alternatives may be to use special command devices or systems : long stick in use in the Russian aircraft, balance of the force-feel system design [12], multi-mode control laws depending on the task/phase of flight...

The X-31 control laws were designed to achieve zero sideslip maneuvers in PST. This design implies little  $G_y$  at the aircraft center of gravity and thus, small lateral accelerations are imposed to the pilot. Also, the normal load factor remains relatively low, because of the low airspeed in the PST domain. As the X-31 is a relatively slow aircraft when compared to modern fighters, high levels of  $+G_z$  may be attained only during the transient phase of increase of angle of attack, during a short time duration. Some transition between  $G_z$  and  $G_x$  also exist when entering PST, but they were not perceived as painful nor disorientating, as the aircraft quickly slowed down and the acceleration remained at moderate levels.

One possible problem of carefree handling may be the lack of sensory cues. Most of the conventional aircraft have some characteristics such as noise, buffet or wing rock which inform the pilot where his current status point is into the flight envelope. In the X-31, the sensory cues (buffet and stick force) are almost the same at 70 degrees as they are at 12 degrees AOA. This led most pilots to ask for a tone to provide them with AOA cueing. Some similar difficulties may exist with other key flight parameters (side slip angle, heading, flight path angle, speed and energy), especially under low visibility conditions. The problem may be more acute as airframe agility and post stall flight relate to parameters which are not primarily monitored under conventional conditions ; special displays and a special training may be required for the pilot to monitor those parameters.

The various unpredicted obstacles discovered and eventually solved during the envelope expansion of the X-31 program suggest that the development of a totally carefree handling system is still questionable, because of the lack of theoretical methods to demonstrate the complete robustness of the handling system, especially under non conventional flight conditions. The only solution, currently applied when expanding the flight envelope of a new aircraft is to proceed with extensive flight tests, which are designed to be as exhaustive as possible given the program cost and time constraints.



#### 4.1.8 Agility metrics

The tools and methodologies currently used in the evaluation of handling qualities provide a large panel of solutions and viewpoints for the evaluation of the practical usability of the airframe agility.

The most easily usable metrics of airframe agility consist of the peak values of some key parameters, such as turn rates, angular rates, accelerations, instantaneous and sustained load factors.

For instance, the turn rate versus Mach number diagram (Figure 6) gives a good picture of the aircraft maneuverability envelope.

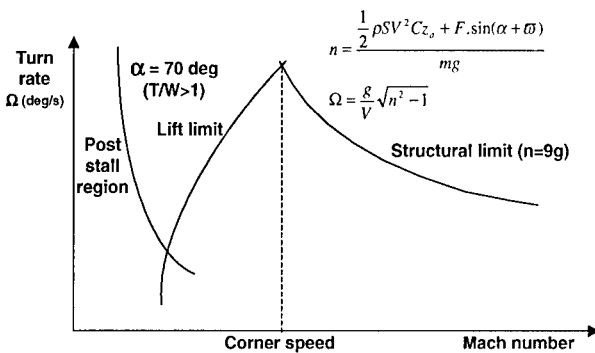


Figure 6 : Example turn rate diagram of a supermaneuverable aircraft.

Some typical orders of magnitude of these kind of parameters for existing and future fighter aircraft can be found in the literature [5, 6, 13, 14, 15].

However, the peak values are not sufficient for a precise analysis of the actual aircraft agility, as they give no information on the dynamics nor on the controllability of the aircraft.

So far, even though relationships between handling and flying qualities are already well-known for conventional aircraft and are subject to standard requirements (MIL-STD-1797 or ADS33), possible conflicts between flying qualities and performance have to be addressed at the design stage when high levels of airframe agility are to be achieved and operationally used [16].

The evaluation may address the following technical aspects : stationary and dynamic behavior of the aircraft under various flight conditions and configurations, ability and ease to perform particular tasks and maneuvers (gross or fine tracking, capture).

The available evaluation tools include numerical and man-in-the-loop simulation, and dedicated pilot's rating, such as the well known Cooper Harper rating scale which has often been adapted to capture the effects of particular features on pilot's control or workload.

The ability to fly at high angle of attack may also require some specific metrics and criteria, as it opens a new

flight domain. Existing metrics have been extended for that purpose and new ones have been proposed [5, 16].

In an attempt to better capture the influence of the airframe agility on the combat effectiveness, some experimental metrics, pilot-centered or mission-oriented, have also been developed.

For instance, the Tamrat's combat cycle time is a measure of the total time duration of a typical combat, described as a cycle of state changes in the Mach number versus turn rate diagram [18]. It has been applied to aircraft capable of flight at high angles of attack and it is particularly useful to assess the aircraft ability to recover its energy after using a post stall maneuver (Figure 7).

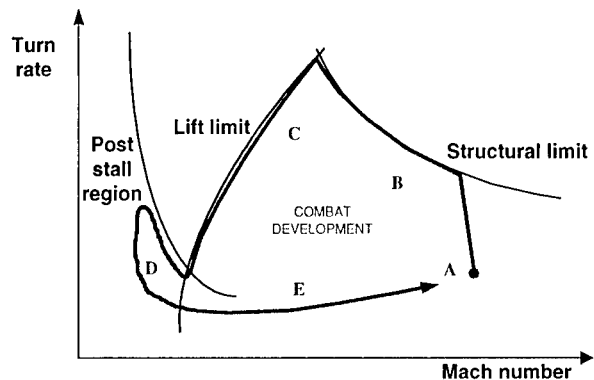


Figure 7 : Typical combat development in the Mach number / turn rate diagram.

This concept of combat cycle is an interesting viewpoint to better understand the cyclic nature of the physical constraints posed on the pilot during an actual fight :

- The combat cycle usually starts at the highest possible level of energy, which means high speed (supersonic) and high altitude, which are acquired as soon as the target is detected. The choice of this starting point (A) depends on the pilot's orders and experience, given numerous factors such as his role in the mission, the type of the target and the environmental conditions. A first shot may be decided at long range, weapons permitting.
- The combat cycle is first composed of one (or several) turns, from level flight at one gee and high speed to the maximum structural or sustainable load factor (B). The aim of this turn is to reach a favorable position relative to the target. It is a prerequisite of any modern engagement. During this turn, the pilot is submitted to sustained load factor at moderate to high level. The duration of this turn in recent fighters may be very long, as the engine power is sufficient to maintain speed even under high load factors.
- The maximum load factor is then maintained and speed decreased up to the maximum turn rate (corner speed), then the speed usually continues to decrease due to the high drag at high angle of attack (C).

- The post stall flight ability may then be used, for instance to point and shoot the target (D). The aircraft is very vulnerable then, as speed is low and maneuverability limited.
- This quick excursion into the post stall region is followed by the reduction of the angle of attack and by an acceleration phase, up to a speed sufficient to reengage a target (E).

The total time needed for the aircraft to cover this typical combat cycle is thought to be a good global indicator of its agility. The physical consequences of airframe agility on a human pilot should be regarded through the characteristics of each segment of this cycle.

## 4.2 Systems Agility

### 4.2.1 Definition and scope

The system agility is defined as the ability to rapidly change functions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.

The systems considered here are individual systems which provide the pilot with tactical information and elaborated functions, rather than low level aircraft systems such as the flight control system which is usually considered as a component of airframe agility, at least in its basic functions.

As such, onboard sensors are of course concerned as they are the main sources in function of information gathering. The countermeasures and electronic war systems may be concerned also as their speed of response is a key of their efficiency.

The off board systems and the ability to share information may also be considered as they play an increasing role in modern scenarios.

The above definition emphasize the only objective of the systems agility which is to help the pilot to achieve his mission. Once again, the pilot-vehicle interface is actually a critical element for the contribution of systems agility to mission effectiveness.

### 4.2.2 Automation benefits and surprises

A high level of automation is necessary for the pilot to control the many complex systems of modern fighters, and it has proved to be mission effective most of the time.

For example, at the border between airframe agility and system agility, some advanced functions of carefree control systems have been developed, where aircraft limits are handled automatically. The automation of the aircraft limits may have some drawbacks under emergency or combat circumstances which require the full use of aircraft, but this problem is only the counterpart of the safety and mission effectiveness

benefits, and the accurate design of the control laws makes it less and less sensitive.

More insidious may be the drawbacks of the automation of higher level functions, also sometimes referred to as automation surprises; while developments in cockpit automation result in workload reduction and economical advantages, they also raise a special class of human-machine interaction problems [19].

These problems have been examined in research addressing the last generation glass-cockpit civilian transport aircraft. They involve confusion on the status of the automated control system and the subsequent behavior of the aircraft. The complexity of the control system is accompanied with a partial knowledge of the system; the pilot's knowledge is focused on the most frequently used automated modes, which may represent only a relatively small part of all the possible modes. A possible mismatch between the pilot's understanding of the system and the actual function performed by the system may occur under unusual conditions. Special training and pilot adaptation are the only compensation for an ill defined automated system and a poorly designed interface.

Although a consensus exists about the need for a feedback of the complex aircraft system to the pilot, special attention should be given to the level of feedback, i.e. the nature and the amount of information concerning the system functions that should be provided, displayed or made sensitive to the pilot.

The complexity of modern systems makes it obviously impossible and undesirable to display every item of information to the pilot, but a minimum level of information is certainly desirable to keep the pilot on line, so that he can take a decision when needed. For instance, information is probably required about the following points: which system functions are actually in control, what are the goals aimed by the system, what to do if a system function fails, and what to do once a goal is achieved.

Also, the level of information provided to the pilot may be context-dependent, as for instance the pilot doesn't always want feedback from the system when the feedback can distract him from the tactical situation. The precise determination of the level of information which is required and sufficient to achieve a mission is not possible today without practical experiments. The research studies about the processes underlying the building of situational awareness could provide some guidelines for the design of future pilot/system interfaces and appropriate pilot aids. Alternative control technologies may also contribute to the enhancement of man-machine communication [20].

The recent approach and development of human-centered automation may help avoid these drawbacks. Nevertheless, the interaction of human with complex system and thus, the contribution of systems agility into mission effectiveness, is still a non trivial problem. The introduction of automation should be driven by actual

operational needs rather than by market or economical considerations.

#### 4.2.3 Emerging technologies

Some technologies contribute directly to increase the systems agility. These technologies provide new capabilities and have a potential to deeply modify the pilot's situation awareness and tactics :

- Extension of the sensors range and angular coverage (radar, infra red, video or laser)
- Fast search mode and reduced update rates (electronically versus mechanically scanned radar)
- Multi tracks and improved classification/identification capacity
- Helmet Mounted Sights/Displays and target designation
- Missile Launch Detector and Missile Approach Warner
- Improvements of Navigation (GPS)
- Communication (high rate datalink) and Collaboration (C3, Third Party Targeting)

For instance, the present days mechanically scanned radar is typically limited to  $\pm 60$  degrees in coverage and cannot track numerous targets due to a relatively low update rate.

The electronically scanned radar and conformal antennas could provide substantial enhancements in terms of coverage, range and resistance to jamming, with direct consequences on the tactics. For instance, an angular coverage extended up to 120 degrees azimuth could allow the pilot to start going away from the target he has just shot, while still illuminating it (F-Pole maneuver).

Helmet Mounted Sights may allow an extension of the coverage to approximately  $\pm 100$  degrees in azimuth and -30 degrees to +80 degrees in elevation, which may considerably modify the way of conducting closed in combat, especially if a target designation is made possible, using head or eye pointing rather than aircraft nose or velocity vector pointing [21].

The improved capacity of future aircraft to automatically share information within the patrol or with other forces or ground support will probably have some very large implications on the way a mission is conducted and on the role of the pilot. The recommended number of seats in an aircraft for a given mission may of course change as a consequence of this new capacity.

More generally, new concepts of task sharing between the vehicles, systems and individuals involved in a combat scenario are being considered and they really have to be in order to get the full benefit from the increasing level of agility of future systems.

### 4.3 Weapons Agility

The weapons agility is defined as the ability to engage rapidly characteristics of the weapons and its associated onboard system. The precision is also mentioned as a critical element of this definition.

The emerging concepts for future weapons include [adapted from 22] :

- Air-to-Air Weapons
  - Expanded envelope (minimum & maximum range)
  - Hypersonic speed
  - Increased off-Axis capability (lock-after-launch using HMS information)
  - Midcourse guidance and improved guidance (seeker performance, thrust vectored control)
  - High angle of attack employment
- Air-to-ground weapons :
  - Enhanced standoff capability
  - All weather capability
  - Improved accuracy
- New weapons
  - Non lethal weapons (especially laser)
  - Multirole weapons (A/A & A/G missile)

For instance, the existing Russian AA-11 Archer short range missile provide some idea of the level of performance that may be obtained with modern air-to-air weapons [23] :

- Off boresight angle at launch up to 60 degrees
- Off boresight angular rate up to 60 degrees per second
- Launcher angle of attack up to 40 degrees

One tactical recommendation for a fighter against this new generation weapon is to avoid the short distance engagement.

Precise weapon agility data is of course usually classified, but one can expect that considerable progress has been made in air-to-air armament since the last large scale conflicts.

These progress are likely to strongly reduce the potential benefits of airframe agility, especially in the close in combat area.

## 5. OPERATIONAL AGILITY

Operational agility is close to the concept of weapon system agility proposed by Boyd in 1988 [5].

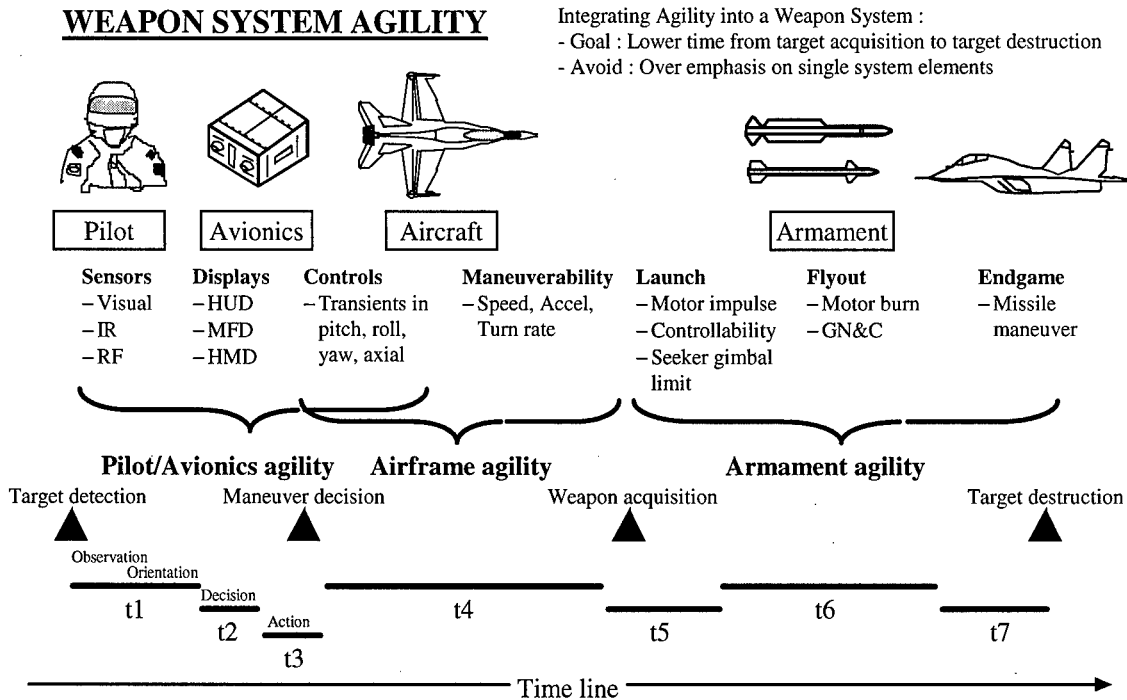


Figure 8 : Weapon system agility [18].

His model (Figure 8) includes seven time delays in the sequence of events between target detection and target destruction, including the Observe-Orient-Decide-Act (OODA) model for the pilot/avionics element.

This simplified model is of course valid only in a given mission context ; it also lacks the role of external support and environmental factors.

However, it illustrates the fact that any gain in the time delays from the detection to the target destruction may be of crucial importance.

Although they are depicted as sequential, the time delays are actually not independent, as all the elements of the weapon system are closely interacting. For instance, the pilot's reaction time depends on the information displayed and maybe from physical factors such as the acceleration level ; also, the attack maneuvers and thus the time required to get a shooting solution depends of the type of missile on board.

A hierarchy of the various components that contribute to operational agility was proposed by Working Group 19 (Figure 9).

The respective agility of each element of the global weapon system contributes at a similar level to the operational agility

In reality, the operational agility results from the correct interactions of all the elements rather than from the high agility of one single element.

Airframe, systems and weapons agility should not be considered separately, as the main contributor to mission efficiency is probably the consistency of the global combat system.

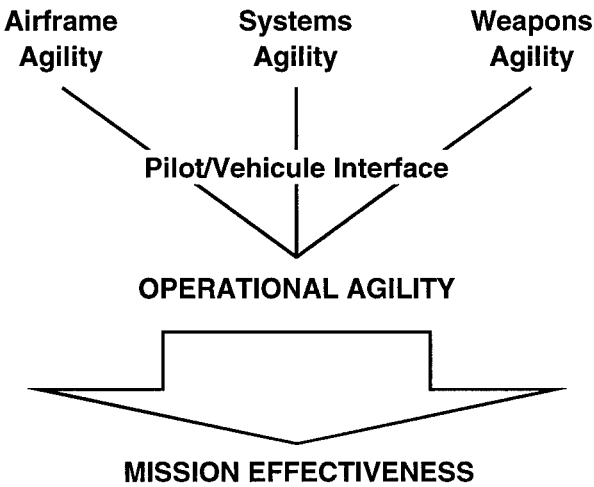


Figure 9 : Hierarchy of operational agility [5].

For instance, enhancing airframe agility by a post stall flight capacity may be useless if the firing systems are too slow to allow a quick shot or if the missiles cannot be launched at high angles of attack. Airframe agility may also become less useful if missile could be shot unlocked at very high off boresight angles, using an HMS.

The balance of the final weapon system and the best trade off between investment and efficiency is the main driver of an aircraft design. Many interesting technologies do exist and will not be applied despite their value because they cost too much and are simply not immediately consistent with the current needs or design philosophy.

Moreover, as long as the pilot is in control of the main tactical decisions, the pilot-vehicle interface will remain a key element into the operational agility hierarchy.

In particular, the potential benefits of high technologies may be impaired if the pilot is not given the tools to use them at best. Also, the introduction of automated functions requires a deep analysis of their potential implications as they may reveal unsuspected drawbacks once in operations.

Ergonomics should be given special attention at the design stage, to ensure that the objective level of operational agility will be attainable by a normally proficient air force pilot.

The following areas of preoccupation related to the issue of pilot-vehicle interaction and operational agility can be listed as follow :

- Physiological : pilot comfort, G protection, angular rates, spatial disorientation,...
- Ergonomics : cockpit, information, displays, controls,...
- Cognitive : workload, situation awareness, pilot assistance, task sharing,...

The operational agility may also require some particular approaches of selection, instruction and training for the next generation pilots.

The human consequences of operational agility have to be considered in the context of the present and possible future operational scenarios.

Those scenarios may present the following characteristics :

- Complex tactical environment with several forces involved : large quantity of information to be displayed and treated ;
- Mission achieved in collaboration with allied forces : flexibility, communication ability and precision required ;
- Various rules of engagement and political pressure : positive identification is usually required which increases risk taking and time pressure ;
- Rapid reaction and localized conflict scenarios, generalization of multirole aircraft concepts with several mission objectives and targets of opportunity : need for a fast decision making ;
- Possible new concepts about the role of the pilot : team work or unmanned aircraft to reduce the exposure to danger ("leave the pilot's head in the aircraft, not the body").

Those characteristics are at the same time a consequence and a motivation for an enhanced operational agility : agility is definitely a requirement in the information era, and its human implications have to be addressed.

## Short glossary

A3A	Aircraft, Armament, Avionics Agility
AOA	Angle Of Attack
BVR	Beyond Visual Range
FEA	Full Envelope Agility
HMS	Helmet Mounted Sight
IRST	Infra Red Search and Track
PST	Post stall flight
SM	Supermaneuverability
STOL	Sort Take Off and Landing
T/W	Thrust to Weight ratio
WG	Working Group
WSA	Weapon System Agility

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